

Prospects for reactor monitoring with noble liquid detectors

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Reactor monitoring with antineutrinos

- Reactor operations may be monitored with antineutrino signals from the reactor
 - Direct information from the core
 - Unshieldable, can not be tampered
 - Non-intrusive monitoring
 - Sensitive to fuel cycle evolution
- Inverse Beta Decay (IBD) is widely used in reactor antineutrino detections
 - SONGS
 - PANDA
 - Chandler
 - WATCHMAN
 - ...



The San Onofre Nuclear Generating Station (SONGS) where reactor monitoring with a Gd-LS detector was demonstrated by LLNL and SNL.

Coherent Elastic Neutrino Nucleus Scattering

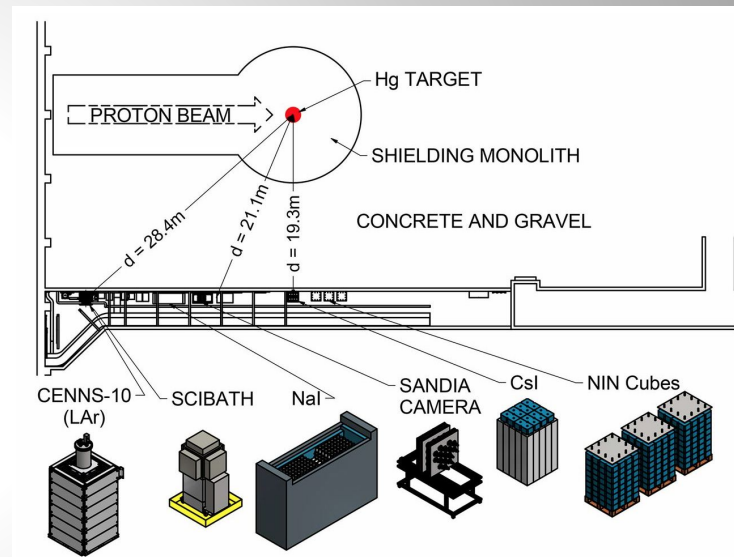
CENNS is a supplemental approach to monitor reactors, possibly with compact detectors.

Advantages:

- High interaction cross section (N^2 enhancement)
- Small detection medium mass
- Small footprint

Disadvantages:

- Low signal energy at reactors (~ 1 keV or lower)
- Possibly high background at ~ 1 keV or lower
- Less neutrino energy information preserved



CENNS was first demonstrated by the COHERENT collaboration at the SNS using CsI targets. [Science, 03 Aug 2017, DOI: 10.1126/science.aao0990](https://doi.org/10.1126/science.aao0990)

Dual-phase noble liquid TPCs

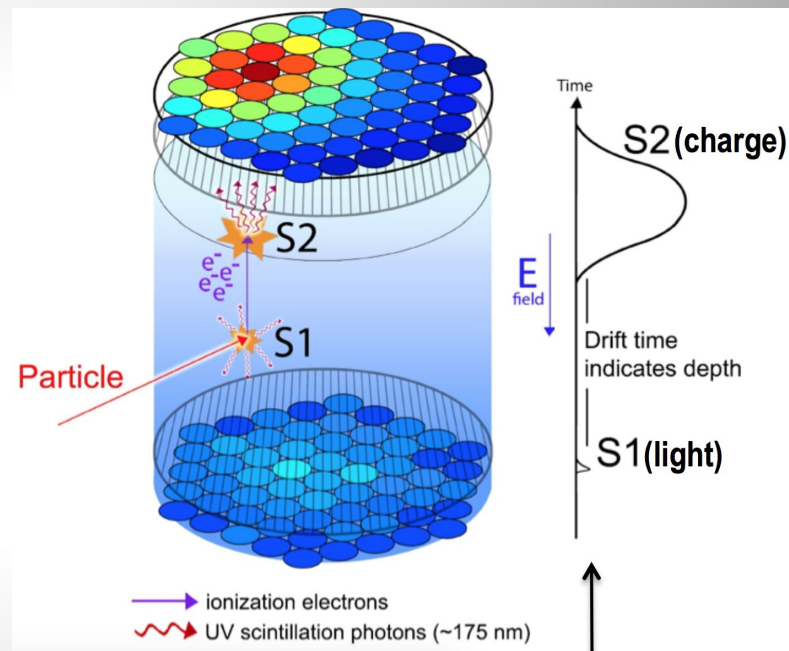
Reactor CENNS signals are similar to WIMP dark matter search signals:

- Nuclear recoils at low energy
- Relatively low event rate

Dual-phase noble liquid TPCs have demonstrated high dark matter sensitivity

- Low radioactivity
- Single electron threshold
- Scalable

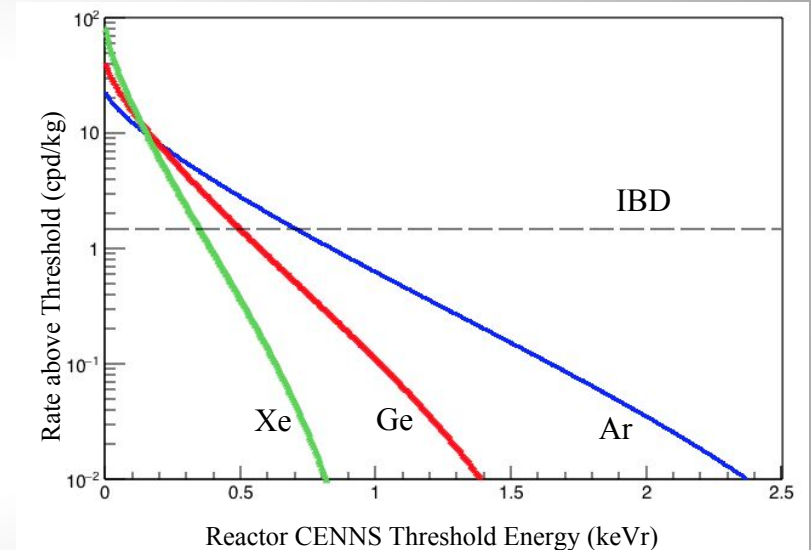
Reactor CENNS requires detection of charge signals only.



An illustration of signal generation in a dual-phase xenon TPC detector. For reactor CENNS events, only charge signals are expected.

Scalability of noble liquid detectors

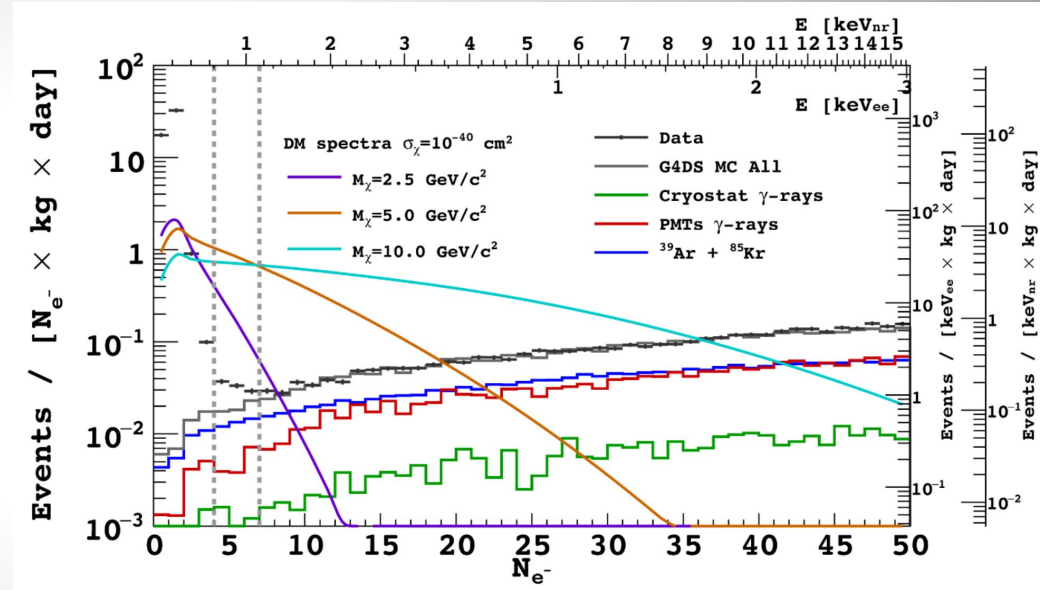
- Current IBD detectors suitable for reactor monitoring are ~ 1 ton or larger
- Ar/Xe/Ge detectors have comparable CENNS rates at ~ 200 eV threshold
- A competitive reactor CENNS detector needs a mass of ~ 100 - 200 kg to have comparable signal rates
- Ar/Xe TPCs are scalable, and may compete with IBD



Estimated CENNS rate in different detector medium for a reactor of 1GW with 25m standoff

Challenges in Ar/Xe TPCs for reactor CENNS

- Nuclear recoil signal at low energies not calibrated
 - <6 keV for Ar
 - <1 keV for Xe
- Background in this energy region not thoroughly studied
 - Radioactive background
 - Instrumental background
 - Cosmogenic background for near-surface operations

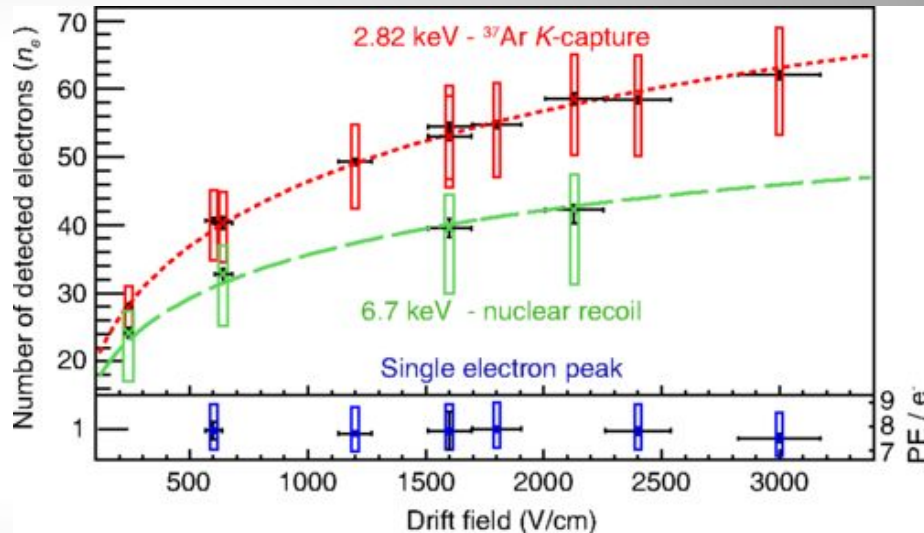


Low-energy spectrum measured by the DarkSide50 experiment -- Note the sharp background increase below 3 e-. [Phys. Rev. Lett. 121, 081307 \(2018\)](#)

LLNL nuclear recoil calibration - Ar

The LLNL noble liquid group carried out the Ar recoil calibration at the lowest energy reported up to data (6.7 keVr)

- Portable dual-phase Ar TPC
- 70 keV neutron beam
- End point measurement
- Field dependence studied



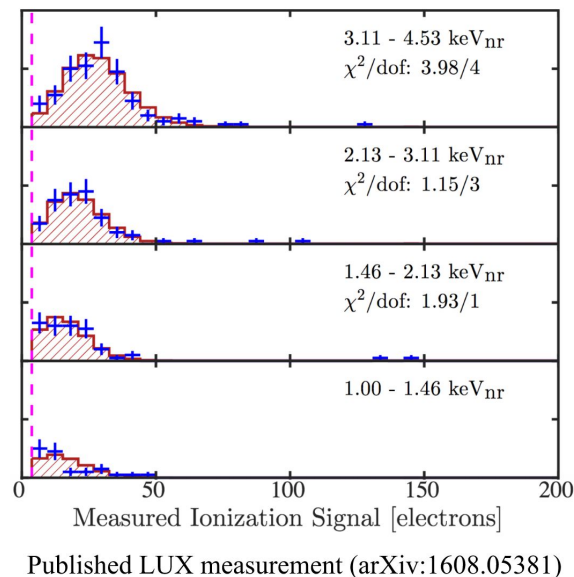
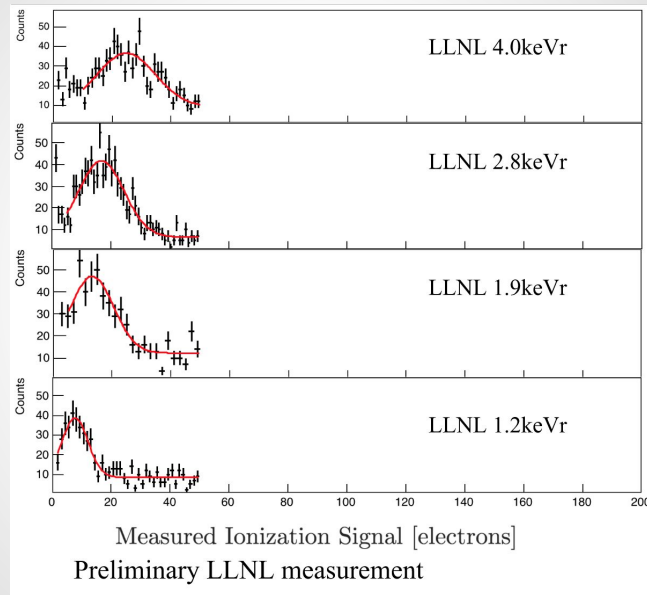
The measured charge yield of 6.7 keVr Ar recoils as a function of drift electric field, measured by LLNL. [Phys. Rev. Lett. 112, 171303\(2014\)](#). The absolute charge scale may have a sizeable uncertainty

LLNL nuclear recoil calibration - Xe

We measured Xe recoils
down to ~ 1 keVr with the
best demonstrated accuracy

- Dedicated dual-phase Xe TPC detector
- DD neutrons (2.4 MeV)
- Backing spectrometry

Lower energy Xe recoil
calibrations underway.



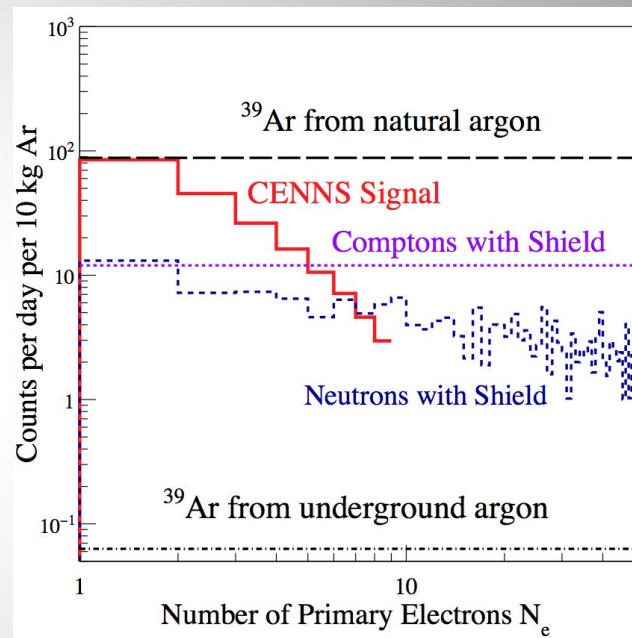
Radioactive background in Ar TPCs

Reactor CENNS signals in Ar TPCs with atmospheric argon will be overwhelmed by ^{39}Ar decay

- Cosmogenic $^{40}\text{Ar}(n, 2n)^{39}\text{Ar}$
- High rate ~ 1 Bq/kg

Argon from some underground sources may have drastically lower ^{39}Ar concentration

- Xu, et al, [Astroparticle Physics 66, 53-60](#)
- DarkSide50, [Physical Review D 93 \(8\), 081101](#)



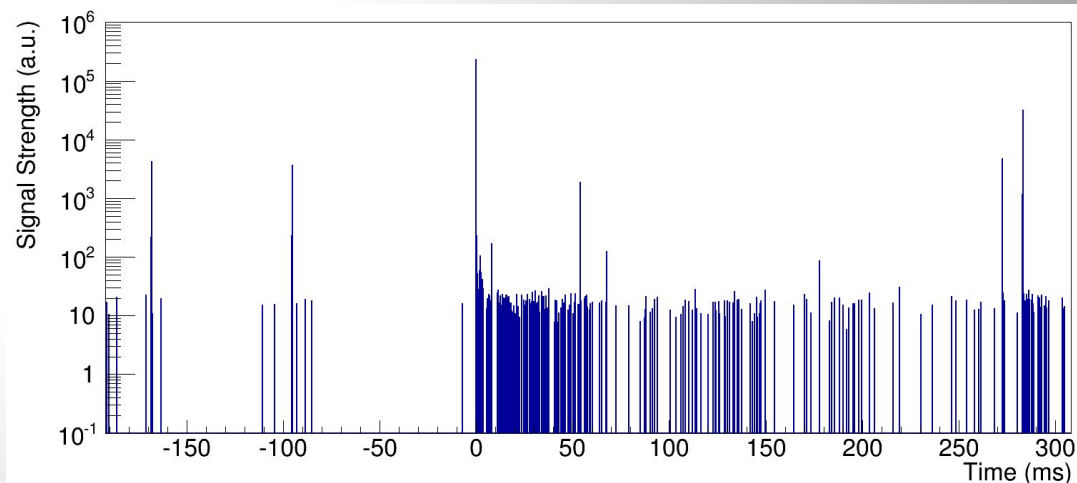
Estimated reactor CENNS rate in comparison with that of background (LLNL). [IEEE Trans.Nucl.Sci. 51 \(2004\) 2151-2155](#)

Instrumental background in Xe TPCs

Xe TPCs have demonstrated 1,000 times lower radioactivity than Ar TPCs due to a) the low intrinsic radioactivity and b) high self-attenuation power.

Xe TPCs observed high instrumental e⁻ background rates

- Impurity-related
- Unextracted electrons
- Photoionization electrons
- Metal surface emissions



Observed electron background in the LUX dark matter detector over an extended period of 0.5s. [APS April Meeting 2016 Volume 61, Number 6, B16.00005](#)

Reactor CENNS with noble liquid TPCs

- ~100-200 kg of Ar/Xe dual-phase TPC
 - Compact footprint ($\sim 1 \text{ m}^2$)
 - Low background rate with sufficient shielding
 - Suitable for surface operation
 - $\sim 2\text{-}3 \text{ e-}$ threshold
- High enough CENNS event rate
 - $\sim 1000 \text{ cpd}$ for 1 GWt thermal power at 25 m stand off
 - Respond to reactor operation interruptions within hours
 - Sensitive to fuel cycle evolution